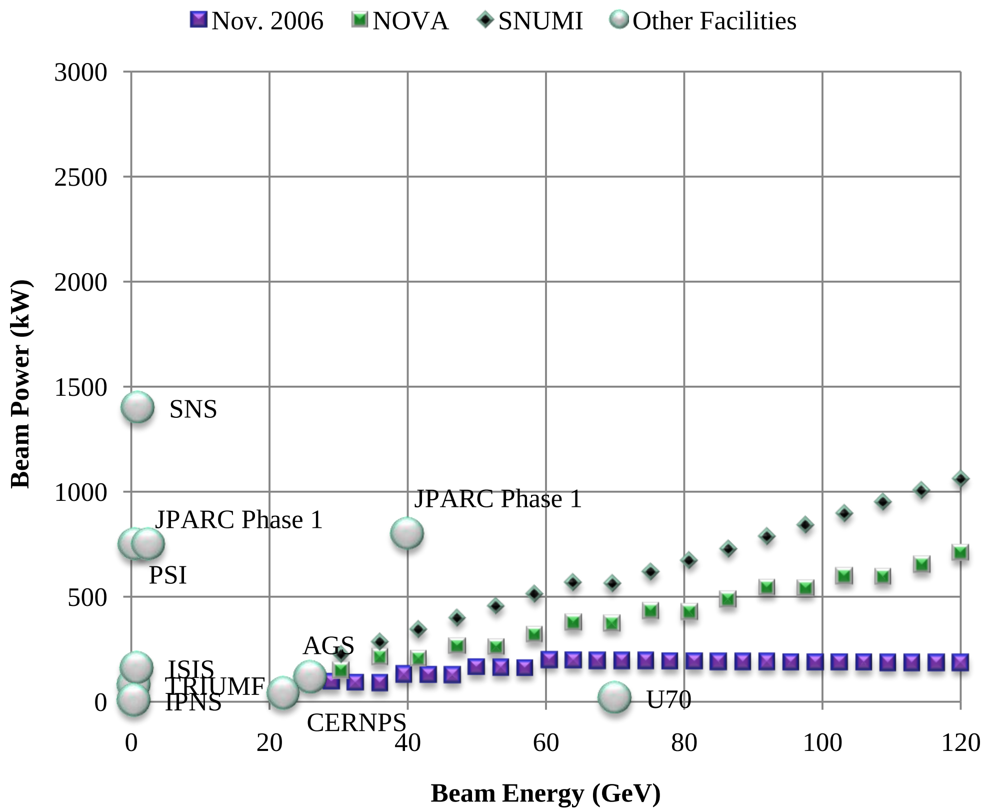
Project X Overview

DOE Program Review

Dave McGinnis

Motivation

- The Fermilab Main Injector has the potential to provide intense energetic proton beams that can unlock discovery opportunities in neutrino physics and flavor physics
- Future neutrino experiments will most likely require beam power exceeding 2MW at energies of 40 GeV and above.
- To provide this intense beam, the proton source must be capable of providing 400kW at the 8 GeV injection energy of the Main Injector.



Motivation

- Currently, the relatively modern Main Injector is fed protons by an aged proton source.
  - The current Fermilab proton source provides on the order of 30kW for the current neutrino program and has the capability of providing up to 70kW.
  - Space charge tune shift at injection into the Booster limits the beam power in the current Fermilab proton source
- Space charge is almost completely mitigated if the proton source is replaced by an 8 GeV Linac.
  - The major issue of an 8 GeV injector linac is cost.
  - Superconducting RF technology raises economic cross-over point between a linac and a synchrotron to the few GeV range.
  - Fermilab Proton Driver design.

Motivation

- One of the key features of the superconducting 8 GeV linac is the synergy it shares with the ILC design.
- Synergy in the designs would help in both directions
- The 8 GeV Linac would benefit from
  - Enormous engineering effort being expended on the design of the ILC main linac.
  - Cost savings resulting from ILC industrialization,
  - Technological advances from ILC R&D

Motivation

- ILC industrialization would benefit greatly from the construction of a superconducting 8 GeV linac.
- The ILC industrialization profile outlined in the RDR calls for each region
  - to double production capacity over a four year program
  - a capacity to produce 25 cryomodules per year at the end of the fourth year.
  - After four years, each region would have produced over 45 cryomodules. (~2% of the ILC)
- The high energy end of the superconducting 8 GeV linac requires about <u>forty</u> ILC-like cryo-modules.
- Construction of the superconducting 8 GeV linac could serve as the impetus for ILC industrialization
- Added bonus of providing a strong physics program with real discovery potential.

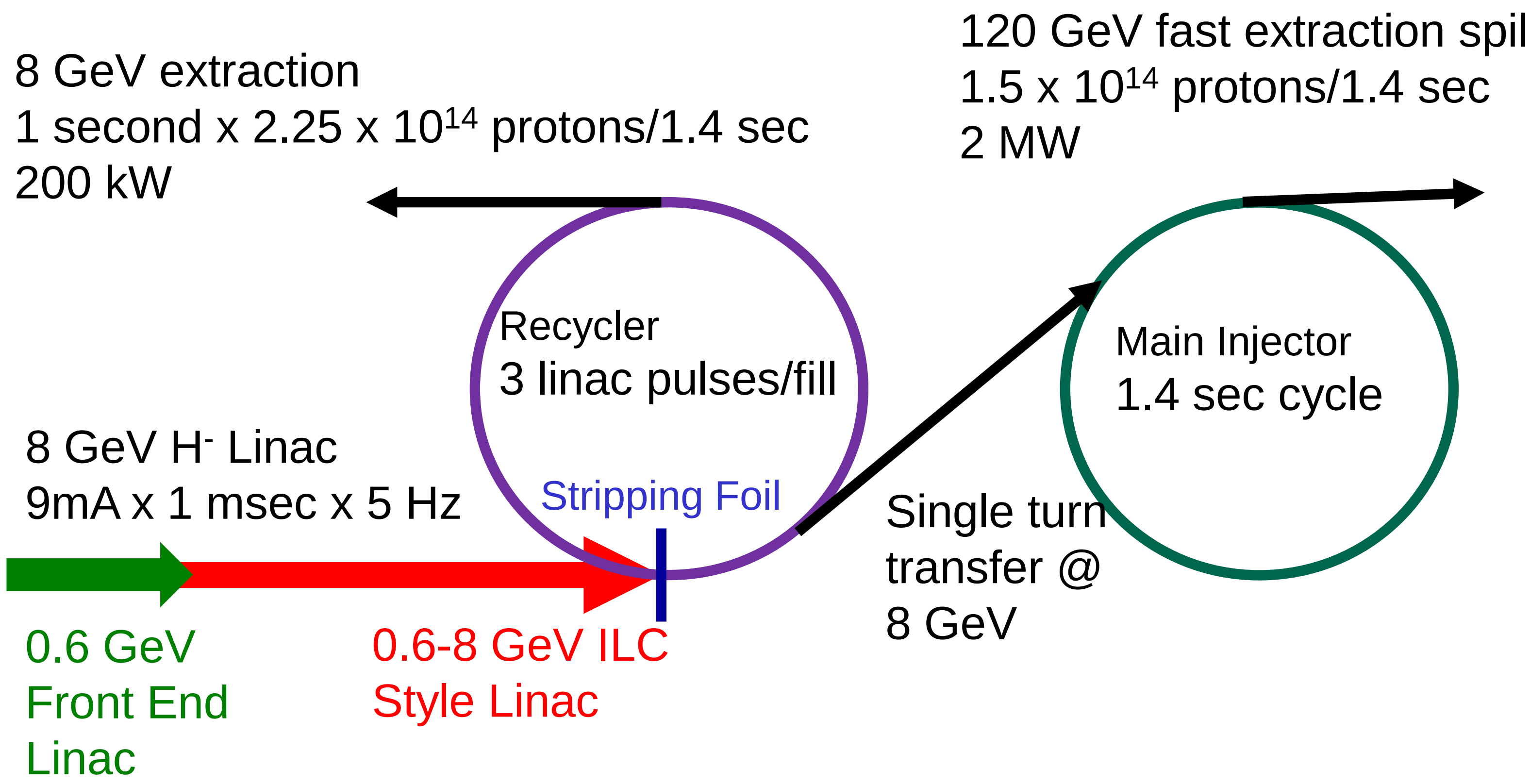
Motivation

- The 8 GeV Linac should be made to look as ILC -like as possible.
  - Same beam parameters
    - 9mA with 1 ms long pulse at a rate of 5 HZ
  - Same configuration
    - Two tunnels
    - cryomodules for $\beta = 1$
    - RF distribution for β=1
    - Cryogenic distribution for β=1
- But 2 MW requires 150x10^{12} protons every 1.4 seconds at 120 GeV
  - 24 mA x 1.0 mS = 150x10^{12} protons (more klystrons)
  - 9 mA x 2.6 mS = 150x10^{12} protons (longer pulse length)
  - 9 mA x 1.0 mS = 56x10^{12} electrons (ILC)

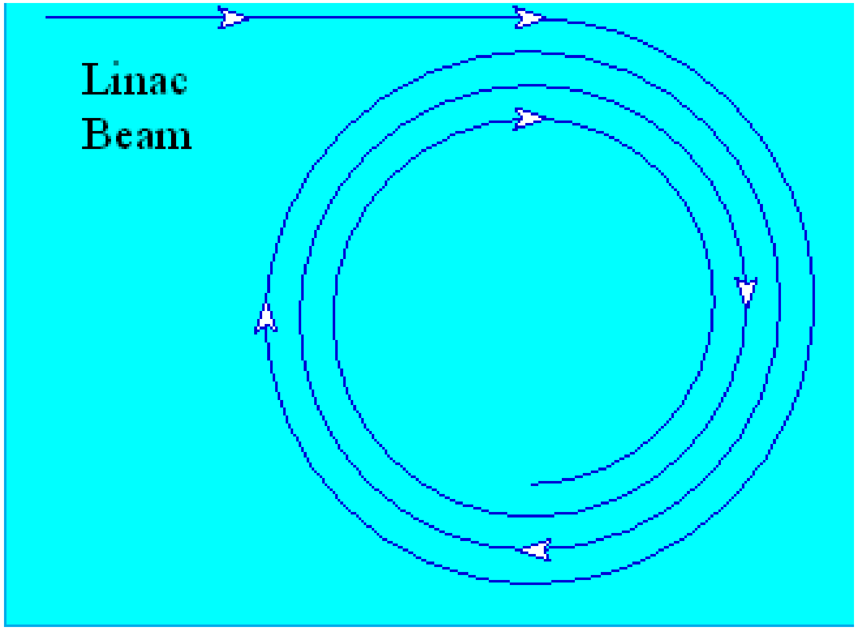
Recycler as a Proton Accumulator

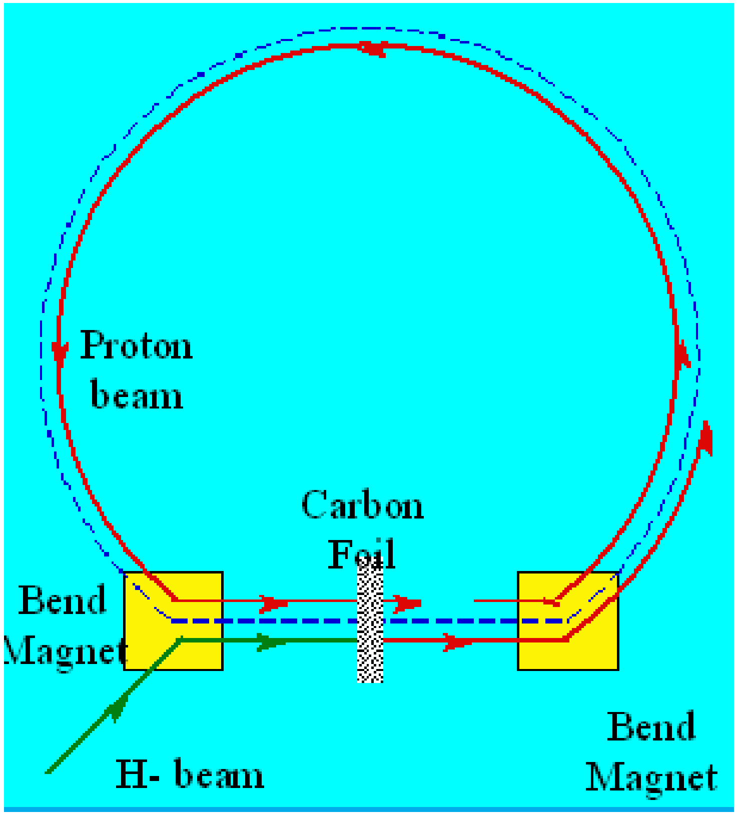
- A holding or accumulation ring inserted between the 8 GeV Linac and the Main Injector can reduce the charge/pulse of the 8 GeV Linac to the same charge/pulse of the ILC linac.
- Feed consecutive pulses of beam from the 8 Gev Linac into the Recycler every 0.2 seconds (5Hz)
  - The H- linac beam is stripped in the Recycler
  - Each Linac pulse is over-laid on top of the previous Linac pulse be re-energizing the stripping system.
- Three Linac pulses is 150×10^{12} protons
- Extract beam from the Recycler and load the Main Injector in a single turn

Project X Layout

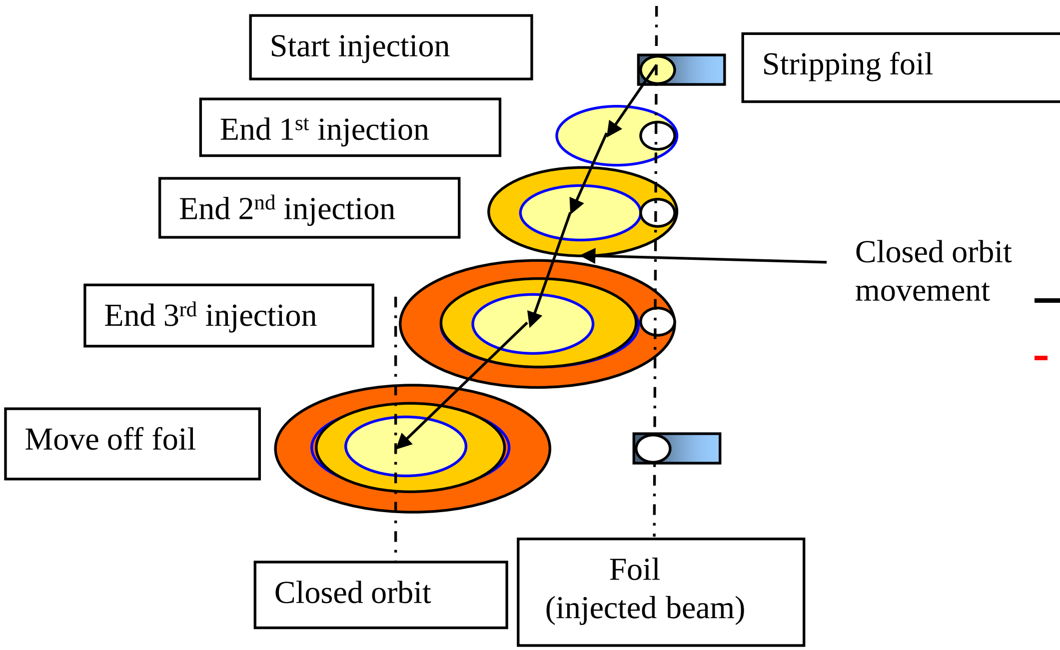


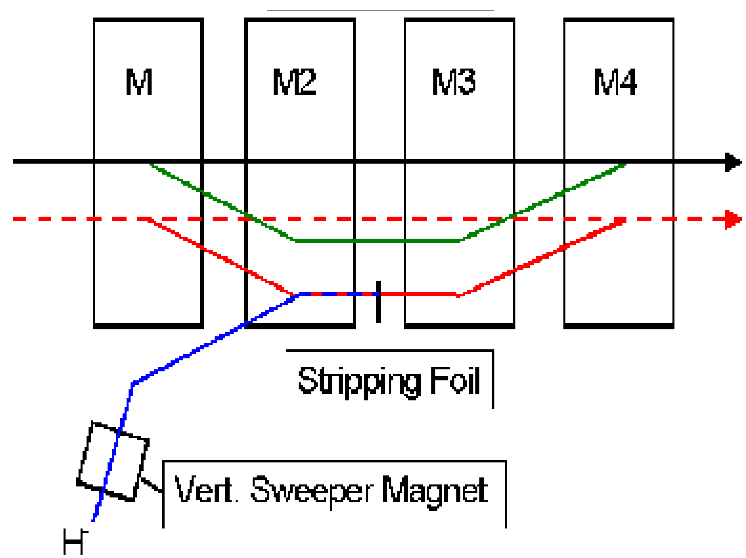
H- Injection


Linac
Beam


Proton
beam
Carbon
Foil
Bend
Magnet
H- beam
Bend
Magnet

Phase Space Painting

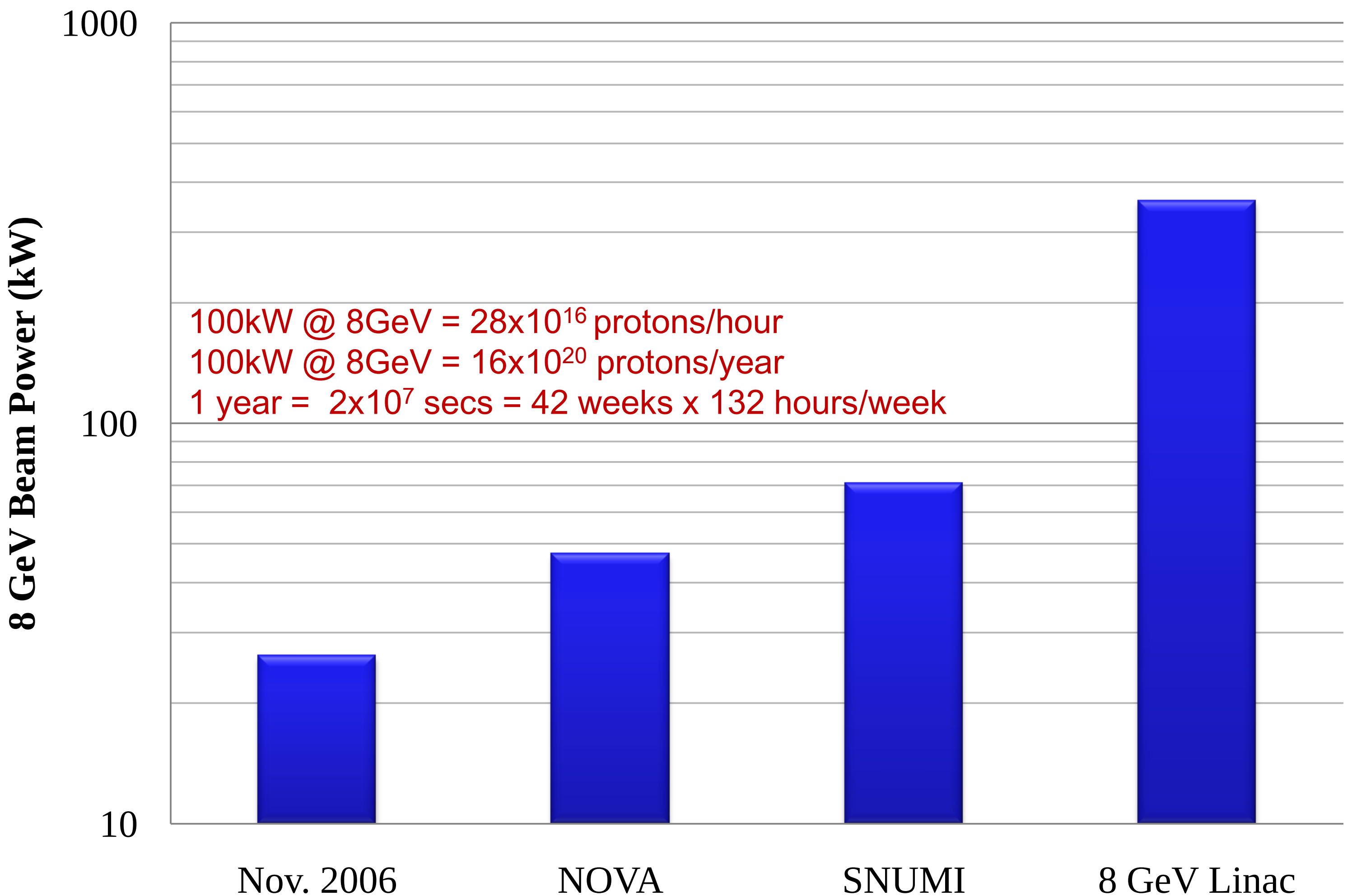




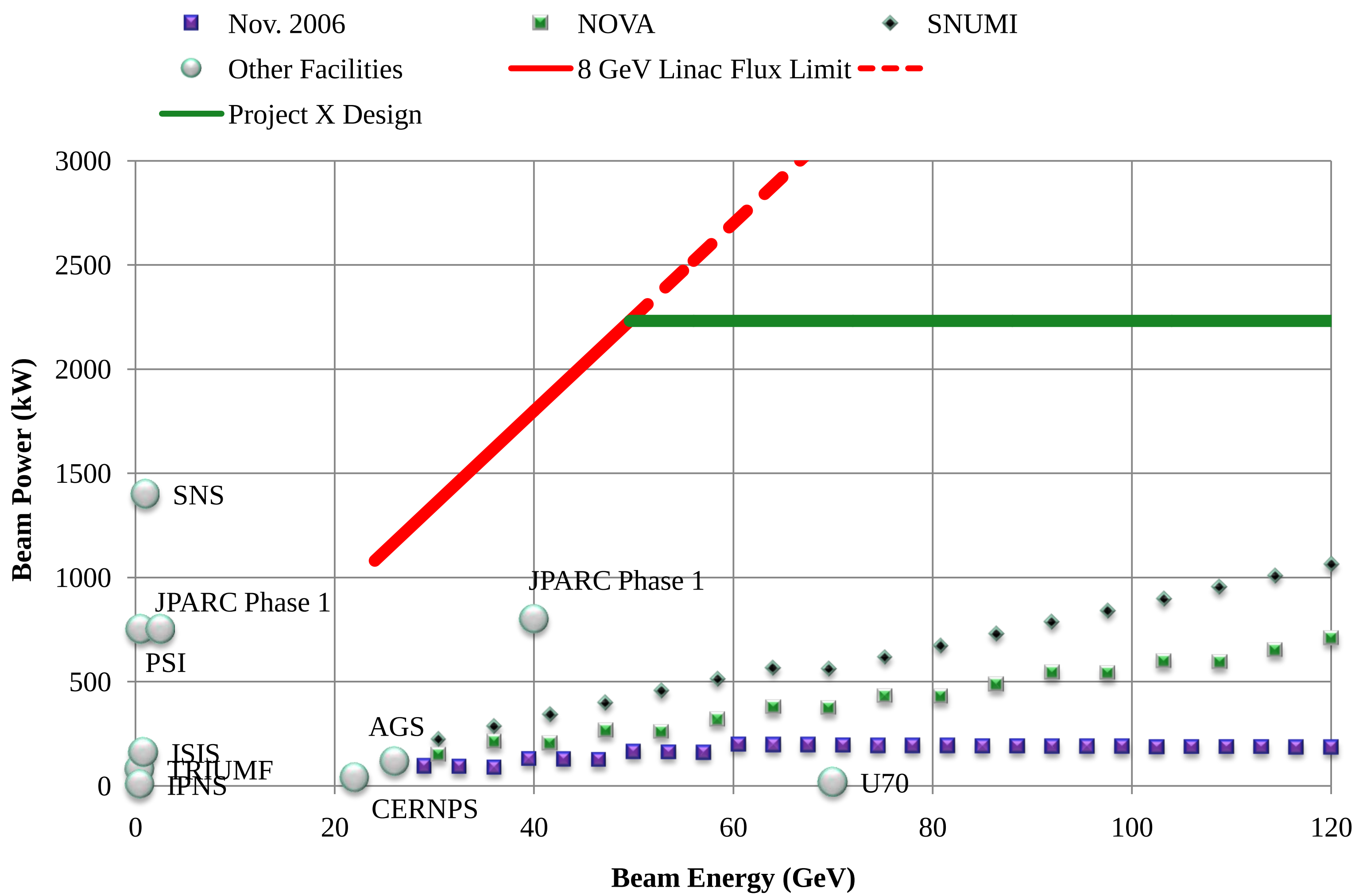
8 GeV Physics Program

- The other advantage to stripping in the Recycler is that the stripping system is available to the Linac while the Main Injector is ramping.
  - There is 0.8 seconds left before the Recycler needs to be reloaded for the Main injector
  - Load and spill 4 pulses for an 8 GeV physics program
- Upgrade Paths
  - 9 mA x 1 ms x 5 Hz = 360 kW at 8 GeV
  - 9 mA x 3 ms x 10 Hz = 2100 kW at 8 GeV
  - 27 mA x 1 ms x 10 Hz = 2100 kW at 8 GeV

Proton Flux


1000
100
10
8 GeV Beam Power (kW)
100kW @ 8GeV = 28x10^16 protons/hour
100kW @ 8GeV = 16x10^20 protons/year
1 year = 2x10^7 secs = 42 weeks x 132 hours/week
Nov. 2006
NOVA
SNUMI
8 GeV Linac

Proton Beam Power



What is Project X?

- The basic scheme is an 8 GeV linac operating with ILC-like parameters (9mA x 1mS x 5Hz)
  - 0.6 GeV Front End linac
  - 0.6 – 8 GeV ILC style linac
- Stripping and accumulation in the Recycler
- Beam distributed
  - to the Main Injector for acceleration to (up to) 120 GeV
  - to an 8 GeV program.
- Components
  - 0.6 GeV Front End linac + 0.6 – 8 GeV ILC style linac
  - 8 GeV transfer line and H- Injection
  - Recycler as a proton accumulator and stripping ring
  - Extraction system form the Recycler
  - Main Injector
  - 120 GeV Targeting system

Schedule

- 2008: CD-0
  - Assume the decision for CD-0 will be quick since this is the only US accelerator project.
  - 6 months of design work
- 2009:
  - Work on (engineering) design report.
  - Start R&D
- 2010:
  - Finish design report. CD-1.
  - R&D on production scale.
  - R&D should be 30% of project costs
- 2011:
  - Preliminary Engineering Design Funding
  - CD2 and CD3
- 2012:
  - Real funding starts: 25% of project funding
- 2013:
  - More construction: 35%
- 2014:
  - "Finish" construction 35%
- 2015:
  - Commissioning & retrofits 5% of project

Timeline

- March 22 – Long Range Steering Committee formed
- May 3 – 8 GeV Stripper ring proposed
- June 6 – Recycler Ring as the 8 GeV Stripper ring proposed
- June 20 – Project X working group commissioned
- August 1 – Project X report due
- August 8 – AAC Meeting
  - "We congratulate the Project X team on an innovative design"
  - "Project-X dramatically increases the high-energy proton power for neutrino experiments, and provides additional 8GeV beam. "
  - "Project-X is especially suitable for Fermilab in the current scenario of a not well-defined schedule of ILC construction, because of synergies with ILC. "
  - "The committee therefore very strongly supports the work that is planned for Project-X."

Project X Report

- Realistic expectations of what could be done competently on a month's time-scale.
- For the August 8 AAC meeting
  - A short report that
    - outlines the concept
    - possible operating parameters.
  - Major technical issues are discussed.
    - There are no show–stoppers with these issues.
  - A plan for future work is outlined.
- Report located at:
  - http://www.fnal.gov/directorate/Fermilab_AAC/AAC_July_07/ProjectX.pdf

Project X Report Acknowledgements

- To proceed quickly on this report, we assembled a team composed mostly of Fermilab personnel.
- But, this report relies heavily on
  - Proton Driver Design report
  - HINS R&D collaboration
  - RIA collaboration
- To move forward on Project X, we will require to continue to rely on the strong collaborative efforts with:
  - Argonne National Lab
  - Brookhaven National Lab
  - Lawrence Berkeley National Lab
- We will also need to develop collaborations with other partners as well:
  - SLAC, JLAB, Cornell

Project X Report Working Groups

- 8 GeV Linac
  - R. Webber – Leader - APC
  - A. Klebaner - AD
  - P. Ostroumov - ANL
  - J. Carnerio - APC
  - (S. Nagaitsev – AD)
  - D. Bogert – APC
  - B. Chase - AD
- 8 GeV Injection
  - S. Nagaitsev – Leader - AD
  - (D. Johnson – APC)
  - J. Lackey - AD
- Recycler
  - A. Valishev – Leader - AD
  - A. Burov - AD
  - C. Gatuso - AD
  - R. Pasquinelli - AD
  - (A. Leveling – AD)
  - (N. Mokhov – APC)
- 8 GeV Slow Extraction
  - Dave Johnson – Leader - APC
  - John Johnstone - APC
  - Mike Martens - AD
  - Eric Prebys - AD
- Main Injector
  - V. Lebedev - Leader - AD
  - I. Kourbanis - AD
  - R. Zwaska - APC
  - D. Wildman - APC
  - A. Leveling – AD
  - N. Mokhov - APC
- 120 GeV Target Station
  - Jim Hylen - Leader - AD
  - Mike Martens - AD
  - Pat Hurh – AD
  - Kamran Vaziri – ES&H

The 8 GeV Superconducting Linac

- Linac Section explores how similar the 8 GeV superconducting linac can be made to the ILC design.
- Major issues are
  - transverse focusing
  - distribution of accelerating gradient along the linac.
- The section
  - presents two sample designs that explore tradeoffs of focusing and accelerating gradient.
  - discusses cryogenic and civil construction issues.
  - relies heavily on the comprehensive Proton Driver design report.

The 8 GeV Superconducting Linac

PROTON DRIVER Ending w/8 ILC RF Units								
Section	SSR-1	SSR-2	TSR	S-ILC	ILC 8pi/9	ILC-1	ILC-2	ILC
End Coordinate	31.4	61	142	227	227	336	336	640
Beta Design	0.2	0.4	0.6	0.8	n/a	1	n/a	1
Output Energy (MeV)	30	120	420	1200	1200	2800	2800	8000
# Cryomodules	2	3	7	7	n/a	9	n/a	24
# Cavities/cryomodule	9	11	6	8	n/a	7	n/a	9-8-9
# quads/cryomodule	9	6	6	4	n/a	2	n/a	0-1-0
Slots"/cryomodule	18	17	12	12	n/a	9	n/a	9
# Cavities (total)	18	33	42	56	n/a	63	n/a	n/a
Max Nom. Accel. Gradient	10	10	10	25	n/a	31.5	n/a	18.3/31.5
# RF Units	325 MHz	325 MHz	325 MHz	2.33	n/a	3	n/a	8

Table 2.2 Superconducting sections of reference linac design with 8 ILC RF Units

PROTON DRIVER w/ 8pi/9 ILC Section								
Section	SSR-1	SSR-2	TSR	S-ILC	ILC-8pi/9	ILC-1	ILC-2	ILC
End Coordinate	31.4	61	188	188	262	373	521	669
Beta Design	0.2	0.4	0.6	n/a	1	1	1	1
Output Energy (MeV)	30	120	603	603	1040	2390	5150	8000
# Cryomodules	2	3	11	0	6	9	12	12
# Cavities/cryomodule	9	11	6	n/a	7	7	8	9-8-9
# quads/cryomodule	9	6	6	n/a	2	2	1	0-1-0
Slots"/cryomodule	18	17	12	n/a	9	9	9	9
# Cavities (total)	18	33	66	n/a	42	63	96	104
Max Nom. Accel. Gradient	10	10	10	n/a	31.5	31.5	31.5	31.5
# RF Units	325 MHz	325 MHz	325 MHz	n/a	2	3	4	4

Table 2.3 Superconducting sections of the favored linac design including $8\pi/9$ mode section

The 8 GeV Superconducting Linac

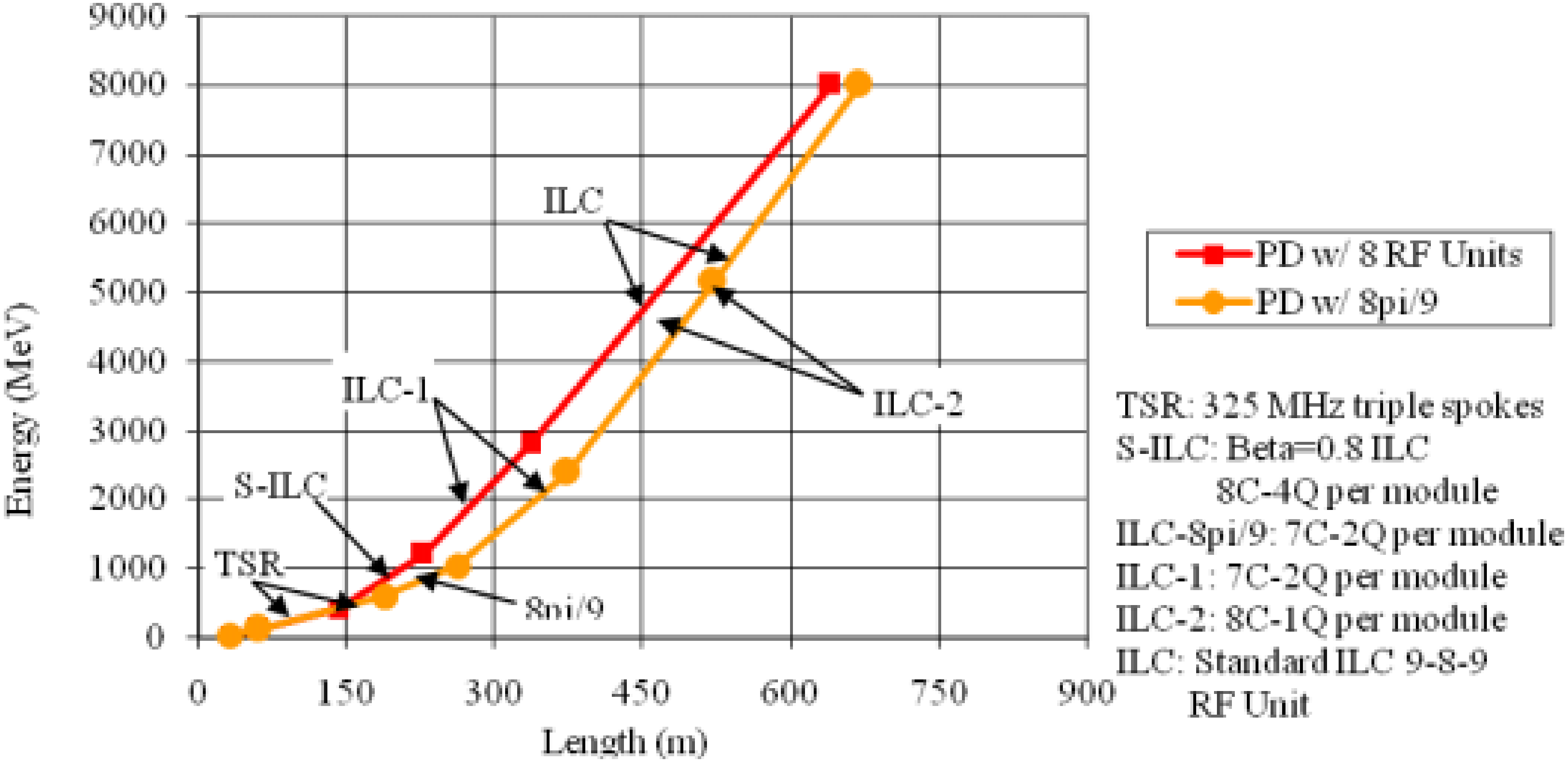


Figure 2.2 Endpoint Energy vs. length for two linac designs

8 GeV H- Injection into the Recycler

- 8 GeV Injection talk reviews and discuss the issues associated with stripping 8 GeV H- ions in the Recycler.
- Much of this work is based on the Proton Driver design report.
- The section discusses
  - Transport between the linac and the Recycler,
  - Techniques for longitudinal and transverse phase space painting,
  - Foil issues,
  - Injection losses
  - Injection absorber.

8 GeV H- Injection into the Recycler

- Previous experience:
  - Fermilab Booster (400 MeV)
  - SNS (~ 1 GeV) plus a collection of others at 800 MeV (LANL)
- The Proton Driver collaboration has performed extensive studies for the injection into MI:
  - H^- Transport and Injection Mini-Workshop Dec. 9-10, 2004 at Fermilab:
  http://www-bd.fnal.gov/pdriver/H-workshop/hminus.html
  - Proton Driver's Director Review: March, 2005
    - Many of the issues raised have been addressed under HINS R&D effort
  - "Found NO show stoppers"
- We have a design for the MI; we can adopt it to the Recycler
  - Fermilab-Conf-07-287-AD "An 8 GeV H- Multi-turn Injection System for the Fermilab Main Injector"
- H^- transport and stripping injection are considered together
  - Fermilab-Conf-06-275-AD "Design of an 8 GeV H- Transport and Multi-turn Injection System"
- BNL collaboration (HINS R&D) in optimization of the foil-stripping injection system
  - Items addressed include, transport line design and collimation, Electron catcher simulations, Foil peak temperature and temperature distribution, and in the future the Chicane magnet design
- Continued carbon foil development (KEK, TRIUMF, SNS)

8 GeV H- Injection into the Recycler

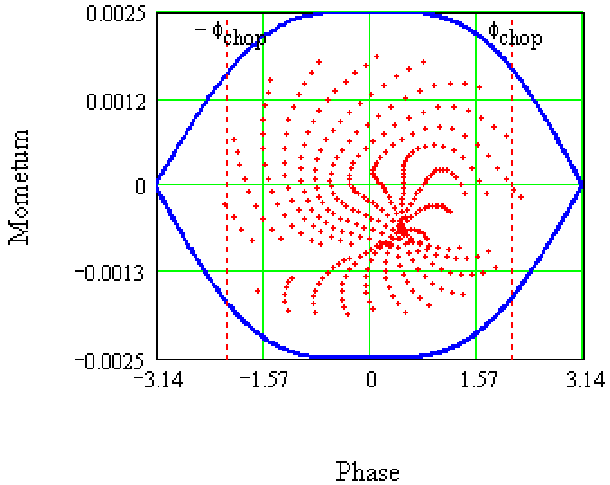
- Future Work
  - Recycler lattice modifications for symmetric injection straight
  - Inclusion of single particle mechanisms into TRACK for loss distribution predictions
  - Design of Recycler collimation of particles with emittances > 40 π
  - Simulation of injection losses/ activation from foil interactions using MARS
  - Painting algorithm looks promising- continue development
  - Injection absorber design looks promising for Project X usage, although we need additional simulation for added beam power
- Conclusions
  - Lower foil temperatures -> good foil lifetime
  - Power supply for painting waveform -> extension from HINS R&D
  - Robust transport line design – can be adapted for Recycler injection
- No show stoppers are seen for incorporating Recycler injection into Project X

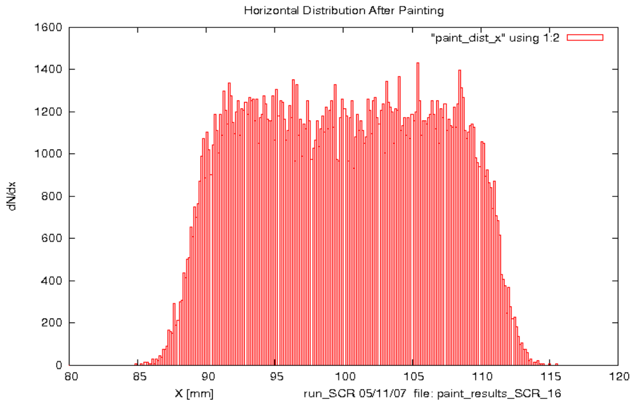
Proton Accumulation in the Recycler

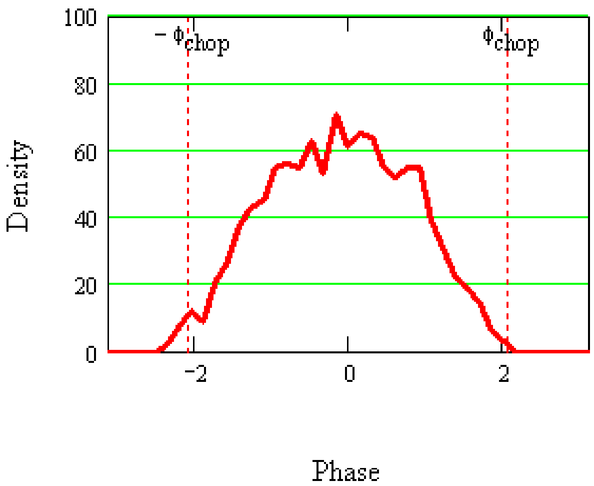
- This section addresses proton accumulation in the Recycler.
- Optimal transverse and longitudinal distributions for minimal space charge tune shift
  - second harmonic in the RF system
  - phase space painting techniques
  - the space charge tune equivalent to present MI operations (<0.05)
- Sources and cures of coherent instabilities for high beam currents in the Recycler and Main Injector.
- Radiation resistance of the Recycler's permanent magnets
- Beam loss management and radiation protection in the Recycler and Main Injector.

Proton Accumulation in the Recycler – Phase Space Painting

- Space Charge Tune Shift reduced to 0.04 due to:
  - Longitudinal phase space painting
  - Transverse phase space painting (K-V distribution)
  - Second Harmonic RF







Proton Accumulation in the Recycler

- No principal limitations from the point of view of accelerator physics have been found for the high intensity operation of the Recycler.
- We foresee no significant modifications to the machine magnets or vacuum system.
- Major upgrade concerns the RF system where the second harmonic system is added.
- Phase space painting is feasible to mitigate space charge effects
- Coherent instabilities can be suppressed by betatron tune chromaticity and broad-band damper

Proton Accumulation in the Recycler

- Under normal conditions total losses should not exceed 300 W (controlled by injection collimation system)
- Recycler permanent magnets are capable of withstanding high radiation doses
- Radiation protection for the project can be realized using Beam loss management
  - Collimation systems and electronic berm are envisaged
- Future efforts could include
  - More detailed lattice and RF design
  - Dynamics simulations with space charge
  - E-P instability studies

Acceleration in the Main Injector

- Acceleration of high beam currents in the Main Injector (similar to B Factory operating currents).
- New RF system
- Gamma-t jump system.
- Coherent Stability
- Local and non-local beam loss.
- Recycler and Main Injector sections share
  - Space charge tune-shift
  - Coherent stability,
  - Beam loss management

Acceleration in the Main Injector – Gamma-t Jump

Gamma-t Jump

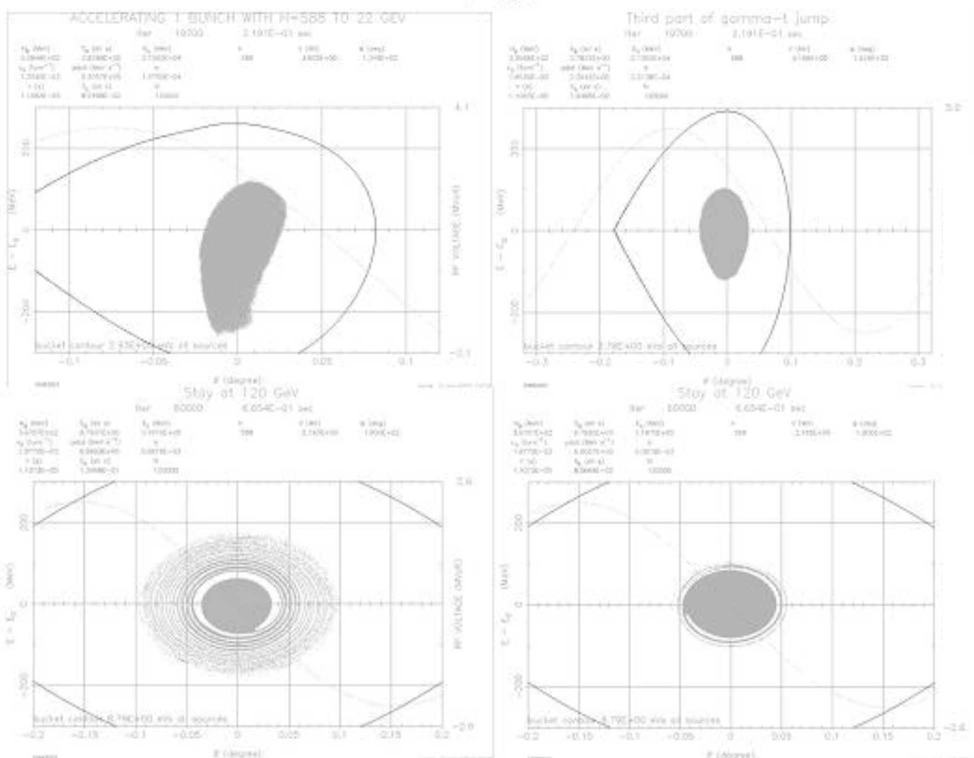
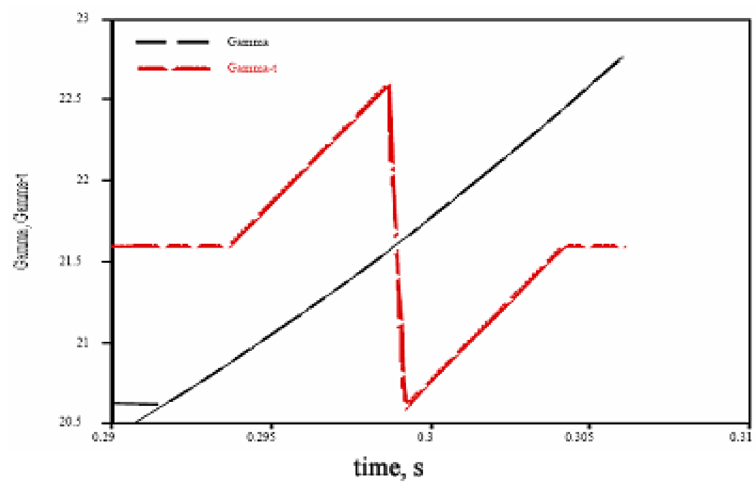


Figure 5.4 Results of ESME simulations of γ_T-jump; top – dependence of γ on time, center - phase space right after transition with (right) and without (left) a γ_T-jump, bottom - phase space at 120 GeV with (right) and without (left) a γ_T-jump.



Acceleration in the Main Injector – RF System

	Present	MI upgrade
Harmonic number	588	
Frequency swing from injection to extraction, MHz	52.811 - 53.103	
Number of cavities	18	18
Shunt impedance per cavity, (R/Q)*Q, kΩ	500	100
Loaded Q	4000	4000
Maximum operating parameters		
RF voltage, MV	4.2	4.2
Peak RF power, MW	3.2	13
Average RF power, MW	0.8	5
Operating parameters required by the presented accelerating scenario		
RF voltage, MV		3.43
Maximum RF power, MW		10.59
Maximum power transferred to the beam, MW		7.32
Maximum power lost in the cavity walls, MW		3.27
Average RF power, MW		4.1

Table 5.2 Parameters of the first harmonic RF system.

	Present	MI upgrade
Frequency swing from injection to extraction, MHz	105.622 - 106.206	
Number of cavities		5
Shunt impedance per cavity, (R/Q)*Q, kΩ		100
Loaded Q		4000
Maximum operating parameters		
RF voltage, MV		1.2
Peak RF power, MW		1.5
Average RF power, MW		0.9
Operating parameters required by presented accelerating scenario		
RF voltage, MV		1.16
Maximum RF power, MW		1.34
Maximum power transferred to the beam[3], MW		-1.83
Maximum power lost in the cavity walls, MW		1.34

Table 5.3 Parameters of the second harmonic RF system

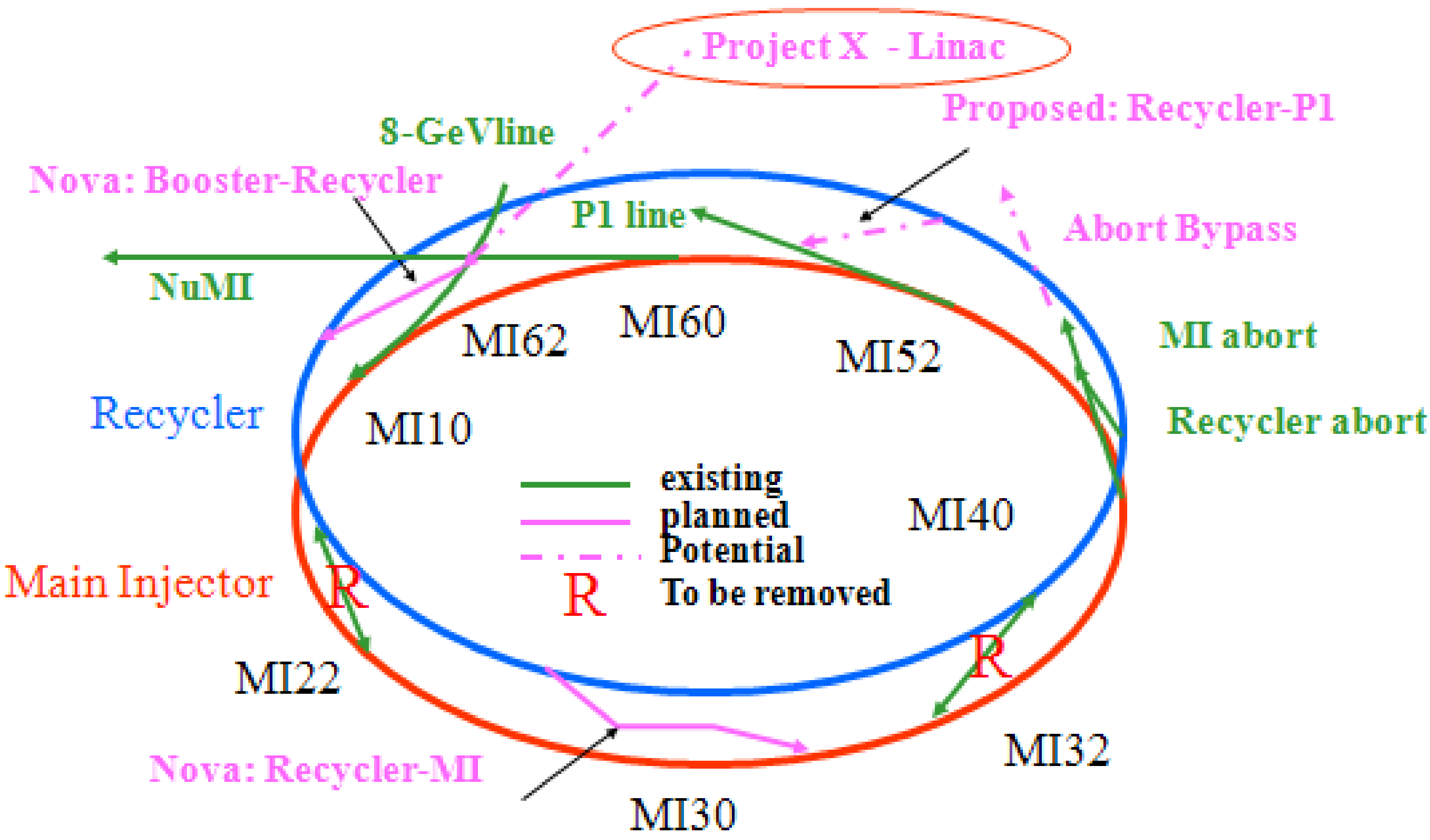
Acceleration in the Main Injector

- There are no principle physics or technical limitations on future machine operation
- ep instability is a major point of concern
  - Simulations show that most likely it will be a problem
  - However, Project X beam current, energy and bunch spacing is similar to the SLAC and KEK B factories
- Keeping the Main Injector operating at 2 MW of beam power with good reliability will be challenging
  - Machine protection and beam loss minimization have to be major points of concern in the next stage of work

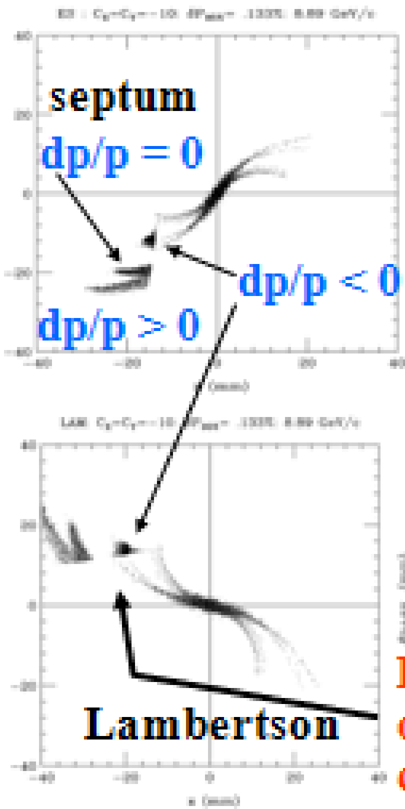
8 GeV Extraction from the Recycler

- Options for extracting beam from the Recycler to an 8 GeV physics program.
- Scenarios for fast and slow extraction from the Recycler.
  - Fast Extraction is straight forward
  - Slow Extraction is difficult
- Technique of transferring beam from the Recycler to the Debuncher ring for slow spill extraction from the Debuncher for the mu2e experiment.

8 GeV Extraction from the Recycler



8 GeV Resonant Extraction from the Recycler



MI (Recycler) 8 GeV extraction

Initial conditions used in simulations:

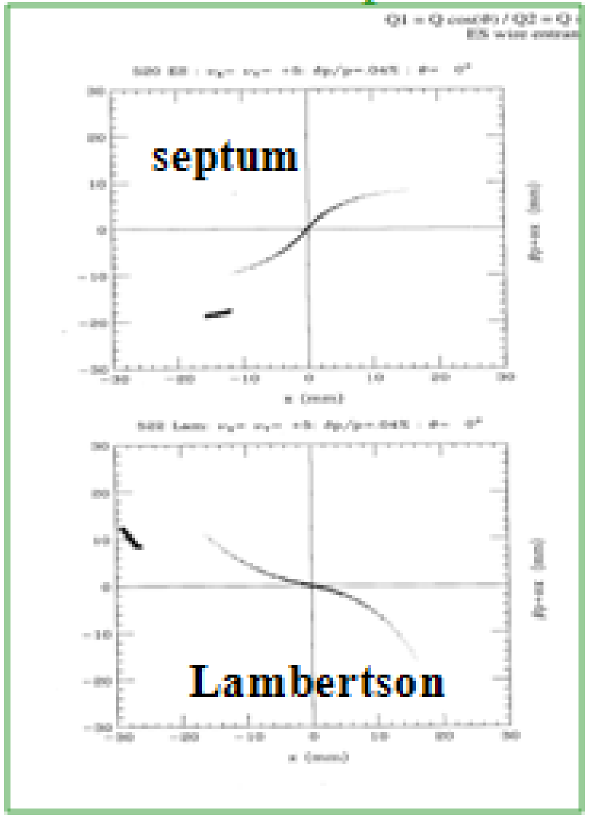
dp/p = -0.155%
0 %
+0.155%

ζx = -10 units
-> $\delta\nu$ = +/- 0.015

Onset of extraction
δ = 0.025
ε = 25 π-mm-mr

Low dp/p extracted beam overlaps high momentum circulating beam: No GAP

For Comparison



MI 120 GeV resonant extraction

- Option NOT VERY ATTRACTIVE, if even possible

8 GeV Resonant Extraction from the Recycler

- Two extraction channels from the Recycler have potential for being developed
  - 52 could supply beam to all existing areas
  - 40 is a new "green field" area that could be developed
- Fast extraction of beam from single bunches to a full ring appear to be feasible (R&D needed for bunch-by-bunch)
  - Resonant extraction in the Debuncher for seems to be straight forward.
- Resonant Extraction from the Recycler does not appear to be attractive
  - More work is needed

120 GeV Beam for Neutrino experiments

- Targeting issues of high power beams extracted from the Main Injector for neutrino production.
- Two possibilities of:
  - A new target hall
  - Upgrading the present NUMI target system.
- No major problems with building a new target system to handle beam powers of 2MW or greater.
- The NUMI system would require substantial upgrades to handle powers greater than 2MW.
  - Uses up redundancy and safety margin of initial NUMI design.
  - Many of these upgrades are complicated by having to deal with activation of components.

Summary

- Project X is an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- The source consists of an 8 GeV superconducting linac that injects into the Recycler where multiple linac beam pulses are stripped and accumulated.
- The use of the Recycler reduces the required charge in the superconducting 8 GeV linac to match the charge per pulse of the ILC design so that much of the ILC technology can be used in the design.
  - This benefit comes at the expense of space charge and stability issues in the Recycler that arise by storing beam in the Recycler.
    - Using transverse and longitudinal phase space painting along with 2nd harmonic RF, space charge tune shift is less than 0.05
  - Although there are many challenging technical issues to building an intense protons source , these issues are surmountable.